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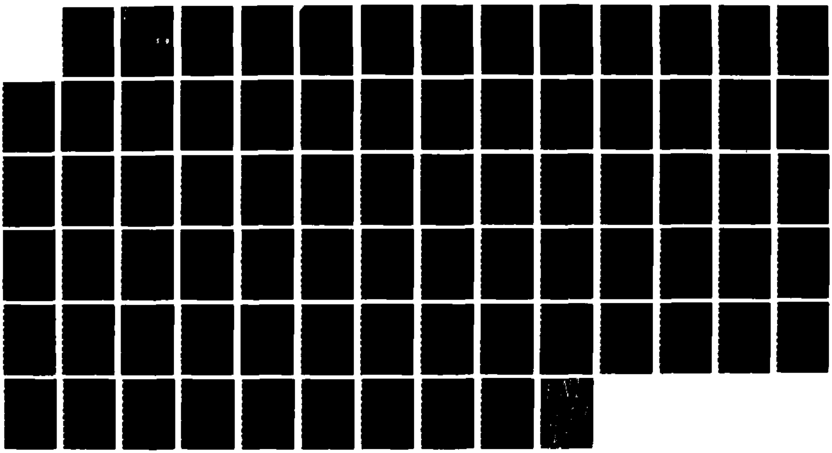

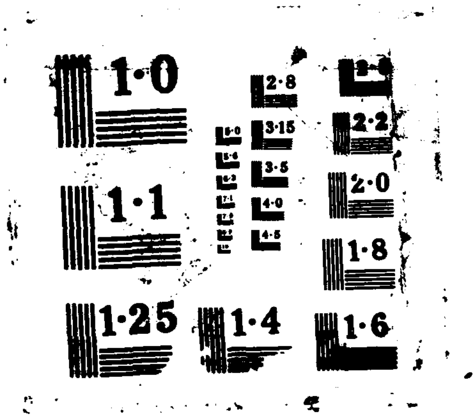
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SPECIFICATION OF PREDICTORS NECESSARY FOR THE DETERMINATION OF OVER OR UNDERESTIMATION OF RADAR DERIVED TOTAL RAINFALL

A Thesis

by

VINCENT PATRICK HOLBROOK, CAPTAIN, USAF

(67 pages)

Submitted to the Graduate College of
Texas A&M University
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August 1987

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SPECIFICATION OF PREDICTORS NECESSARY FOR THE DETERMINATION OF OVER OR UNDERESTIMATION OF RADAR DERIVED TOTAL RAINFALL

A Thesis

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August 1987

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ABSTRACT

Specification of Predictors Necessary for the Determination of Over or Underestimation of Radar Derived Total Rainfall. (August 1987)

Vincent Patrick Holbrook, B.S., Texas A&M University
Chairman of Advisory Committee: Dr. George L. Huebner

A study was performed to produce a set of empirical predictors useful in identifying over or underestimation of radar determined rainfall rates. Two radar sampling procedures, systematic and irregular, were employed against light and heavy rain events to calculate rainfall rates for 10 km x 10 km grid boxes. Sampling intervals used were 10, 15, 20, 30, 40, and 50 minutes. The sampled rainfall rates were compared against the rainfall rates for 5-minute sampled data and the error was determined. The predictors were then used to determine whether the error was an over or underestimation.

There was no significant difference in results as a function of the sampling interval used. Different sets of predictors were required for the category of precipitation as well as over or underestimation.

The percentage of correct identifications, whether for over or underestimation, approached 80%. Allowing for error associated with the 5-minute sampling interval, the correct decision approached and sometimes exceeded 90%. The predictors which produced the best results utilized percent coverage of the grid box by precipitation, temporal and spatial homogeneity, and the mean rainfall rate.

DEDICATION

To my wife Diane, whose support and understanding were essential in this endeavor.

ACKNOWLEDGEMENTS

The author wishes to express sincere appreciation to Dr. G. L. Huebner for extending his time, devotion, and expertise to the completion of this study. Gratitude is also extended to Dr. R. C. Runnels and Dr. R. J. Freund for their united contribution to this research effort.

In addition, many thanks go out to Mr. Jerry Guynes for the assistance he provided in the programming aspect of this research.

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1. INTRODUCTION

a. Overview

The conventional, non-coherent radar, through the use of empirically derived relationships between rainfall rates and reflectivity, provides a reasonable accurate estimate of rainfall over large areas (Battan, 1973). The use of these relationships require several assumptions which, when not met, result in error. The assumptions violated the most often are: (1) the illuminated volume is uniformly filled with scatterers, (2) microwave attenuation between the radar and the target is negligible, and (3) the scatterers are homogeneous, dilectric spheres (Huebner, 1985). The errors associated with these types of problems are difficult to estimate or control. On the other hand, errors associated with the time interval between radar scans can, under certain conditions, be somewhat controllable (Wilson, 1976). This is possible in that the total rainfall is an integration with respect to time of the radar derived rainfall rates. Since storms lack homogeneity, move at varying speeds, and are rarely steady state, lengthening the sampling interval increases the possible error.

Studies made by Fornear (1985) and Zdenek (1986) produced excellent procedures for the determination of radar derived errors as a function of the time interval between radar scans. Fornear showed that statistical errors resulting from a scan interval of 5 minutes or less are 5% or less. The results were enhanced by the work of Zdenek in that quasi-random time periods as well as various grid areas were added to the previous work. An improvement in the statistical analysis was possible because of Zdenek's use of a 5-minute interval as an assumed correct value. By using this interval one tape could record 400 minutes of data. In this way, studies could be done with the storm length as an added variable. Although the results were statistically

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The citations on the following pages follow the style of the Journal of the Atmospheric Sciences.

reliable, both suffered from the fact that the results were presented as absolute values of errors and no procedure was evident that could determine whether or not the error in a particular case was an over or underestimation.

The deficiencies in the previous approaches provided an opportunity to develop a procedure that could give a statistically correct answer as to whether an over or underestimation occurred.

b. Objective

The objective of this research was to develop a set of predictors which could identify either over or underestimation of radar derived rainfall for each 10 km by 10 km box of a 150 km by 150 km grid. The predictors were then used in a "decision tree" method to improve results. Also investigated was the relationship between the predictors and the category of precipitation, sampling procedure, and the sampling interval utilized. Questions to be answered by this research include the effect temporal and spatial homogeneity, mean rainfall rate, area coverage by precipitation, and other variables associated with rainfall have on the determination of the sign of the error.

This research was intended to help radar operators identify the sign of but not the magnitude of the error. Some predictors were selected since they could most easily be observed by an operator. Other predictors which require computer aided processing of radar information were also developed.

c. Previous research

Wilson and Brandes (1979) noted that sampling error reduces the accuracy of radar observations. It was determined that the problem associated with a large sampling interval was the failure to adequately sample radar reflectivity variations that are important for the determination of rain deposition. Also, it is obvious that an improperly calibrated radar system as well as the use of an inappropriate Z-R relationship are sources of error. For sampling

intervals greater than five minutes the error in total rain deposition increases rapidly (Fornear, 1985).

Fornear, using the one minute radar sample as an assumed correct value, obtained results which agreed with Wilson. Mean absolute values of error ranges from 8% to 45% for sampling intervals ranging from 15 to 60 minutes. For sampling intervals of five minutes or less the error was less than 5%. The variables with the highest correlation with error were sampling interval and number of samples. Other variables such as mean rain rate, storm width, speed, and depth, showed only poor correlation with error.

Finally, Zdenek (1986), using the 5-minute sample as an assumed correct value, developed error curves depicting error as a function of the number of samples. The sampling intervals ranged from 10 to 50 minutes.

Neither Fornear nor Zdenek produced results that indicated whether the predicted error, as a function of sampling interval and procedure, was an over or underestimation of the true value of total rainfall over the designated area. Wilson (1976) used rain gage data as ground truth and stated that radar derived total rainfall tended to overestimate heavy rainfall and underestimate light rainfall.

2. PROCEDURE

a. Data collection and initial processing

Digitized radar data, recorded from the WSR/TAM-1 10.3 cm wavelength radar, was collected for six rain events. The information obtained from the radar was digitally recorded on a 9-track tape using a Digital Video Integrator Processor (DVIP). The information provided by the radar was an averaged reflectivity which could be converted into either rainfall rates or rainfall. The DVIP divides the information into 1 degree wide by 1 km keep bins and processes information from 20 km to 450 km from the radar by integrating the power return over 15 radar returns.

This study was particularly designed to develop a set of predictors which could determine if an over or underestimation of the radar determined rainfall rate occurred. Studies by Wilson and Brandes (1979) and Fornear (1985) showed that there was only a small difference between rainfall determined from 5-minute sampling versus continuous sampling so the 5-minute data was assumed to be a correct value. This allowed for recording of rain events for as long as 400 minutes.

The rain events were selected in order to obtain a data base which represented the natural variability associated with radar derived rainfall. The total number of 5-minute scans per event ranged from as few as 24 to as many as 60 with some events consisting of line type activity while others were just large areas of rain. Limiting the number of events to six was due primarily to the problem of handling the voluminous amount of data. The rainfall events were equally divided into two categories of precipitation, light and heavy, with 12 mm of total rainfall being the dividing point between the two categories. Utilizing a video playback unit, each event's cell and area movement, average depth, and number of scans to process was determined. Table 1 is a summary of the six rain events. Since this research was an extension of both Fornear's (1985) and Zdenek's (1986) research, previous decisions concerning method of collection of data were the same. For all rain events, only radar information from the northwest

quadrant (270-360 degrees) from the radar site was processed with the maximum range being 212 km. Ground clutter was avoided by not using any data from within a 60 km circle from the radar. To reduce the possibility of processing when anomalous propagation was occurring radar echoes which persisted during all scans were eliminated. Finally, all processing of data was stopped once the leading edge of precipitation entered the ground clutter pattern. This accounts for the difference in the number of scans that Zdenek processed for each rain event and the number processed during this research.

Table 1. A brief description of the six rain events.

Julian Day	Year	Number of 5 minute scans	Area Speed km/hr	Average Depth km
34	1986	44	30	40
99	1986	36	60	25
100	1986	24	30	15-30
120	1986	24	50	25
133	1985	60	40	40
169	1985	44	25	15

The recorded data was processed in two ways. First, a data base was created which consisted of, by sampling procedure, the percentage by which the rainfall was either over or underestimated for each grid fox. Second, the data extracted from the radar information was stored by grid box to later identify if an over or underestimation occurred. Finally, some data was eliminated from the data base if the number of scans per grid box exceeded a critical value. Using each storm's recorded data for each scan, the range bins' DVIP value was converted into the linear form Z (mm^6 m^{-3}). The Z-values were then assigned to an appropriate grid box thereby effectively converting the R-Theta system used to record radar information into a X-Y cartesian system.

The cartesian system consisted of a 150 km x 150 km regime of 225 10 km x 10 km grid boxes. The number of range bins per grid box decreased as the distance from the radar increased. The Z-values were later converted into rainfall rates, R (mm/hr), using the Marshall-Palmer relationship ($Z = 200\ R^{1.6}$) and stored in a three dimensional array with subsequent scans read and processed in a similar manner.

b. Variable selection

In order to identify either over or underestimation, a three level approach was used, utilizing the recorded Z-value of each range bin, to develop variables which could be used by a set of predictors. The three levels consisted of the individual grid box, a small area around and including the grid box, and the entire quadrant. The variables developed from one level would then be compared to those of the other levels. For instance, the mean rainfall rate of the grid box was compared to the same parameter obtained from the large area. Before introducing the variables which were developed from the range bin Z-values, a further explanation about the three levels will be given.

The first level used the range bin Z-values from each 10 km x 10 km grid box. The number of range bins per grid box was a function of the distance from the grid box to the radar. Grid boxes closest to the radar contain more than 100 range bins while the boxes farthest from the radar contain as few as 28 range bins. Individual range bins which cover more than one grid box are, in this process, forced into only one grid box. This means that what was defined as a 10 km x 10 km grid box was of variable size. This should not affect later results.

The small-area level idea was a result of the failure of a different approach. Initially, this level was designed to utilize radar data to take a "snapshot" of the storm just as it entered the grid box. But, many problems arose which could not easily be overcome. First, a reliable estimate of the storm motion was required. Unfortunately, storms within the same quadrant moved with varying speed and direction. Combining this inconsistency with new cell development or dissipation resulted in the inability to derive a storm motion applicable to all

grid boxes. One could determine storm motion individually for the over one thousand grid boxes but this was deemed too cumbersome.

It was then decided to use a small area around the grid box as a substitute for the snapshot method. This small area had to be large enough to encompass the entire storm that passed over the grid box yet small enough to yield variables different from the large area. Since the largest average storm depth was 40 km it was decided to set the small-area size to a 50 km x 50 km square area centered on the grid box. The data was then extracted from the 25 grid boxes which composed this area when the storm system was halfway through the grid box. One major limitation was that grid boxes near the edge of the 150 km x 150 km quadrant could not be used in this approach since part of the small area would have been outside the grid system. Also, for similar reasons, grid boxes near the ground clutter pattern could not be used.

As mentioned before, the large area consisted of the entire 150 km x 150 km square area with the exception of the ground clutter pattern. It is expected that the large area may not be as helpful with the problem of identification of over or underestimation but since the data was available it seemed wise to use it.

Out of the 225 boxes originally composing the quadrant, 36 were in the ground clutter pattern. This left 199 boxes in the large area and only 86 available to the small-area level. A diagram of the 150 km x 150 km grid showing the ground clutter pattern, large area, and small area is shown in Fig. 1.

The variables developed from each level will now be discussed. For each grid box and by each sampling interval the number of scans used were recorded. It was important to know these times since the variables themselves must use the same data from which the sampled rainfall was determined. For example, if scans number 5 and 7 were used for a certain grid box, when using a 10-minute sampling interval, only these two scans' data were used when developing the variables. Remember that each grid box could have been used by up to six different sampling intervals so the data was determined and stored by each sampling interval.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
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*	*	*	*	*	*	*	*	*	+	+	+	+	+	+	15

Fig. 1. An illustration of the 150 km x 150 km area used in this research. Each grid box represents a 10 km x 10 km area. The +'s represent the ground clutter pattern while the *'s indicate the boxes which can not be used by the small area level. The ⊛ represents the location of the radar and the numbers are used to differentiate between individual grid boxes.

Variables from within the grid box were developed from each scan and for all scans. From each scan, the spatial mean rainfall rate and standard deviation, the percent coverage of the box by precipitation, and the frequency of occurrence of DVIP levels one through six was determined. The range of values for each DVIP level is given in Table 2. For all scans, the variables were the temporal mean rainfall rate and standard deviation, the temporal coverage by precipitation, the frequency of occurrence of each DVIP level, and the maximum DVIP level which occurred. If a grid box was only scanned once the temporal mean rainfall rate and standard deviation could not be determined.

Table 2. The range of Z-values for each of the six DVIP levels used in this research.

Level	Z-value (mm^6 m^{-3})
1	10-888
2	889-11670
3	11671-35380
4	35381-107253
5	107254-464639
6	464640-1000000

Variables developed from the small area were the spatial mean rainfall rate, a summation of all of the range bins according to the six DVIP levels, and the maximum DVIP level which occurred. The small area data was extracted from the scan which was half the time between the first and last scan. The small area consisted of 25 grid boxes which may have eliminated some of the temporal variability of the storms contained within the area.

The large area's parameters were the same as the small area with one important exception. The data used by the large area was a temporal average from all scan times used by the grid box method. Thus, the

mean rainfall rate of the large area was a temporal average of a spatial rainfall rate. This was done to filter out the temporal variations accompanying the rain event.

Two different sampling procedures were used during this research. These were a systematic and an irregular sampling procedure. One of the objectives was to determine how or if the ability to predict over or underestimation was affected by the sampling procedure. The sampling intervals used for each sampling procedure were 10, 15, 20, 30, 40, and 50 minutes. The 15-minute sampling interval was used since more variability was expected in the smaller sampling intervals.

In the systematic sampling procedure, the time interval between sampling was a constant. For instance, if a 20-minute sampling interval was employed and rain occurred in the box from the fourth through the thirteenth scan then the fourth, eighth, and twelfth scan rainfall rates were totalled. This sampled rainfall was averaged to give an average rainfall amount per 5 minutes and then multiplied by the number of 5-minute scans, or in this case multiplied by ten. This result was then compared to the rainfall obtained from the ten 5-minute scans. The ratio of the sample derived rainfall to the 5-minute rainfall minus one was calculated. This yielded a percentage difference from the original assumed correct value of rainfall with an overestimation being a positive quantity and underestimation negative. An underestimation could never be greater than 100% while there was no bound to overestimation.

In the irregular sampling procedure, the scan processed was either 5 minutes before or after or the actual scan used by the systematic procedure. Using the previous example, when the systematic procedure used the eighth scan the irregular procedure would use either the seventh, eighth, or ninth scan. But the first occurrence, or in this example the fourth scan, of rain was not used to derive the sampled rainfall. There were two reasons for this. First, the random number generator used to pick the scan may have picked a non-existent scan. Second, a radar operator using the irregular sampling procedure could not be assured that the first sample found with rainfall was the first time rainfall occurred in the grid box. Thus, the second sample of the

grid box was used as the first time rain had occurred. As in the systematic procedure, the percent error of the sampled rainfall to the 5-minute rainfall was calculated for all grid boxes. All rain events were processed in a similar manner in order to develop a data base in which the set of predictors would identify whether the grid box precipitation was over or underestimated.

c. Data elimination

One of Fornear's conclusions was that sampling precipitation within a grid box more than eight times during an 80 minute period resulted in a mean error of less than 5 percent. Since the amount of data obtained from the six storms was so large any grid box which met or exceeded the above criteria was eliminated from the data base. This only affected the 10 and 15 minute sampling intervals and, as Table 3 indicates, only a small amount of data was actually eliminated.

Table 3. The percent of data eliminated from the data base.

Sampling interval	SAMPLING PROCEDURE			
	Systematic		Irregular	
	Light	Heavy	Light	Heavy
10	1.2	2.4	1.1	2.0
15	0.7	0.2	0.2	0.2

Fornear used a systematic sampling procedure with a one minute sampling interval as the assumed correct value. Did Fornear's conclusion apply to the data from these events? Table 4 verifies that his conclusions was indeed correct. For a systematic procedure very little error was observed while in the irregular procedure the error was somewhat higher but certainly tolerable.

Table 4. Mean error of the data eliminated from the six rain events.

Intensity	Systematic	Irregular
Light	2.5	6.7
Heavy	4.6	11.8
Combined	3.9	7.5

3. PREDICTOR DEVELOPMENT AND RESULTS

Predictors were developed from the variables obtained from within the grid box, small area, and large area. For both over and underestimation the initial set of predictors were tested against the data base. Predictors which failed to properly identify the sign of the error were either eliminated or redefined. Thus, a reduced set of predictors was formed from each initial set. The predictors of the reduced set were then used in combination with each other to improve results. Finally, pairs of predictors which worked well together were used in combination with the rest of the predictors.

a. Storm classification

Before identifying the predictors, the reason why storms were separated into a light and heavy precipitation category will be discussed. Zdenek (1986) classified storms as either light or heavy as a function of the amount of precipitation which occurred during the entire time the rain event was being scanned. His criterion between the two categories of precipitation was the occurrence of 12 mm of radar estimated rainfall in any grid box. It was not known if the distribution of error between light and heavy rain was different or if it was if it would result in a significant difference in the ability of any predictor to identify over or underestimation. Therefore, it was decided to separate the rain events by these two categories in order to note how the predictors were affected.

In order to qualitatively illustrate the difference between the light and heavy rain events Figs. 2 and 3 were developed. Fig. 2 displays frequency of occurrence versus error by sampling interval for the light rain events which were systematically sampled. Note that in the 10-minute sampling interval most of the error was within 10% of no error. Increasing the sampling interval increased error. Also, the tendency towards underestimating rainfall becomes more pronounced as the sampling interval increased. Fig. 3 was the same as Fig. 2 except

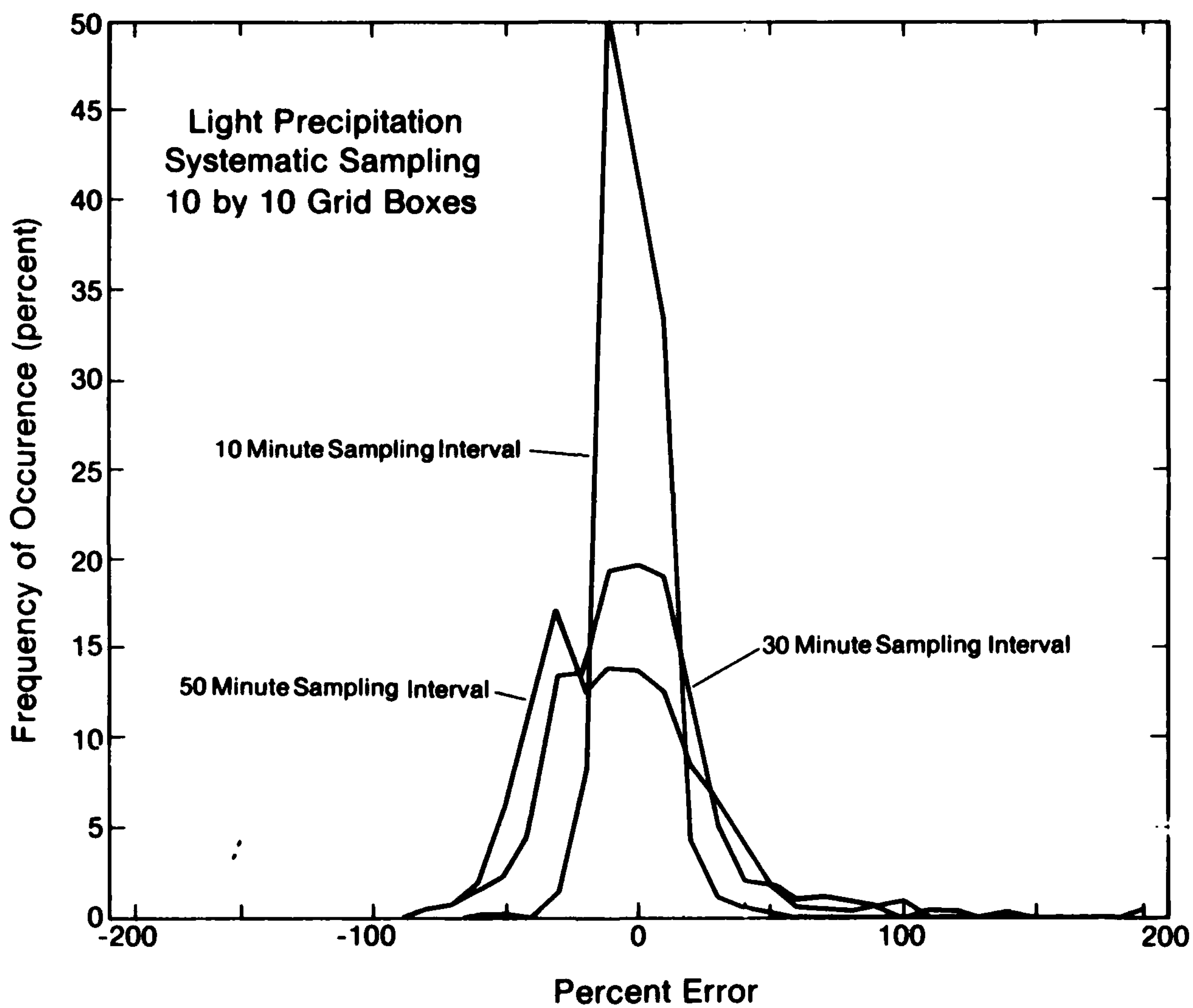

Fig. 2. Frequency of occurrence versus percent error for systematically sampled light rain events for 10, 30, and 50 minute sampling intervals.

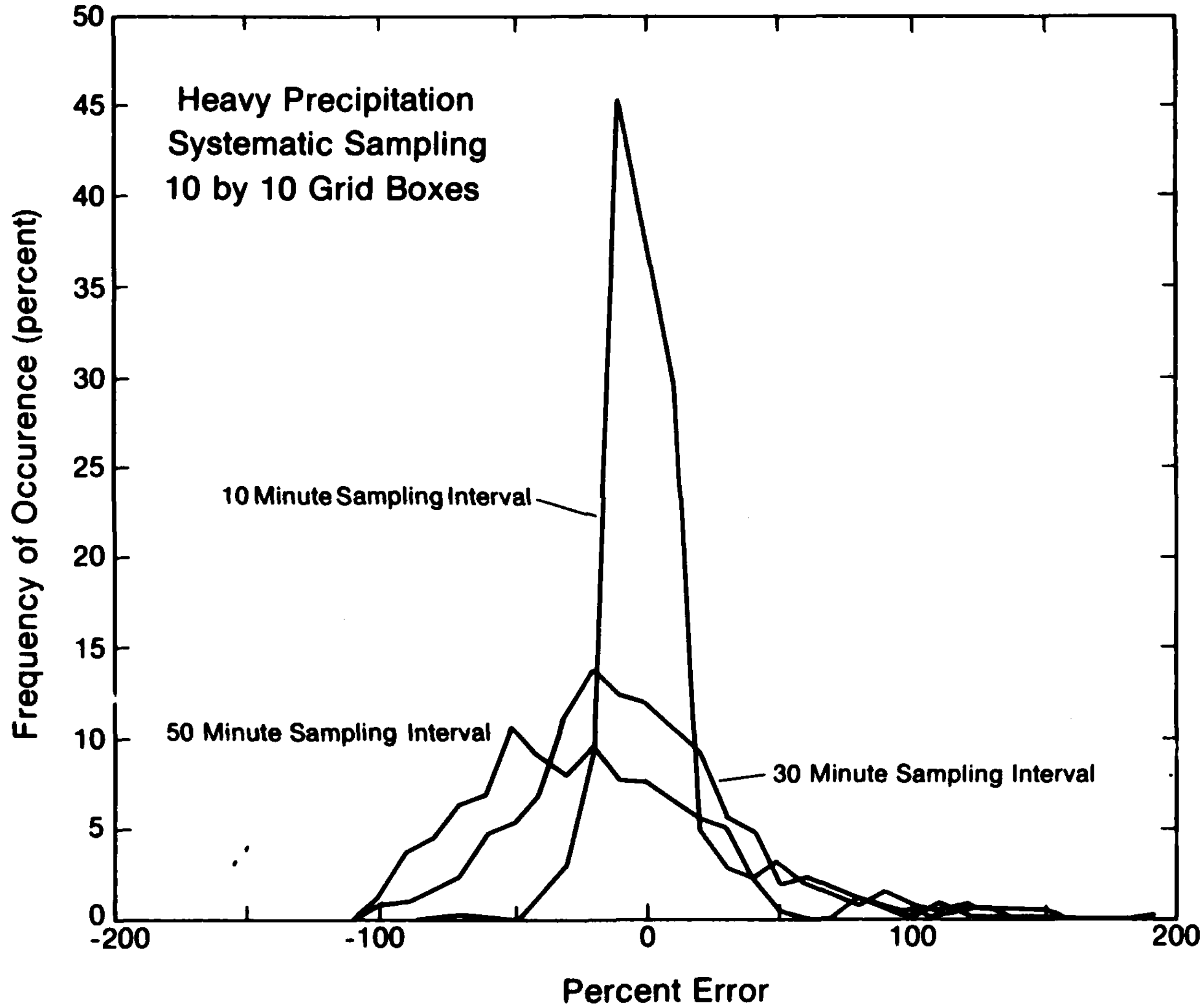

Fig. 3. Frequency of occurrence versus percent error for systematically sampled heavy rain events for 10, 30, and 50 minute sampling intervals showing error associated with heavy rain events.

this displays error associated with heavy rain events. Similarly, the error curve of the 10-minute sampling interval was within 10% of no error but with a 50-minute sampling interval the frequency of occurrence was about the same for a large range of error. In both light and heavy rain events the tendency to underestimate was well pronounced in the larger sampling intervals. Similar results can be shown when using an irregular sampling procedure.

Now quantitative evidence will be given to further show the differences between the light and heavy rainfall categories. In light rain, 54% of the grid boxes' rainfall was underestimated while in heavy precipitation this increased to 59%. By sampling procedure, 56% of the systematically sampled grid box rainfall was underestimated while the irregular procedure accounted for 58%. The difference between the category of precipitation was significant but the same could not be said for the sampling procedure. Table 5 shows the percent of grid box rainfall underestimated according to category of precipitation and sampling procedure. Only in light rain, irregularly sampled does there appear to be an even distribution of error. In heavy rain events, as the sampling interval increased the tendency towards underestimation increased, while for light rain this pattern was not as well defined.

Table 5. The population statistics from the six rain events given by sampling procedure and category of precipitation.

	PRECIPITATION			
	Light		Heavy	
	Systematic	Irregular	Systematic	Irregular
Underestimated	55	54	60	58
Overestimated	45	46	40	42

b. Initial set of predictors

1) Underestimation

The predictors initially thought to be useful in identifying underestimation will now be presented. The predictors account for spatial and temporal homogeneity, mean rainfall rate, area coverage, as well as improper sampling. The importance of each predictor will be discussed.

The first three predictors utilized the temporally averaged percent coverage of the grid box by precipitation. This percentage was obtained by first calculating for each scan the ratio of the number of range bins with precipitation to the total amount of range bins in the grid box. This ratio was then averaged for all scans. The three predictors covered different ranges of the percent coverage. These ranges were less than 30%, more than 30% but less than 65%, and from 65% to 90% coverage of the grid box by precipitation. Studies by Wilson had indicated that light rain was usually underestimated. The three categories were designed to identify areas of light rain. Typically, the outer edge of the rain area, whether or not the precipitation category was light or heavy, was the probable location of the lighter rainfall. In addition, if the main storm does pass over a grid box but was not scanned at the time of maximum coverage then, for that grid box, the resulting temporal coverage by precipitation would be lower than normal. In either situation the result could possibly be an underestimation.

The next two predictors were dependent upon the first scan of the grid box. For one predictor, the criterion needed to identify the grid box as underestimating precipitation was less than 65% spatial coverage. The other predictors' criterion was that the variance of the spatial mean rainfall rate was larger than a given critical value. The critical values are listed in Appendix B. The use of the variance was an attempt to incorporate homogeneity of a storm as a predictor. A mean rainfall rate which exhibited large variance was a signal of a non-homogeneous system. The precipitation for homogeneous systems was

thought to be underestimated. Differences between the systematic and irregular sampling procedures were expected for these two predictors since they did not use the same scan as the first scan. Therefore, the importance of failing to capture the leading edge of the precipitation was being investigated.

Four predictors were developed using the temporal mean rainfall rate for each grid box and comparing this to the spatial mean rainfall rate of the small and large area. The temporal mean rainfall rate of the grid box was calculated by averaging each scan's spatial mean rainfall rate. For the first two predictors, if the grid box mean rainfall rate was less than the small or large area an underestimation was indicated. The other two predictors were similar except that, for the small area and large area, one quarter of their respective mean rainfall rates was subtracted from both before the comparison was performed. This resulted in the comparison of the grid box mean rainfall rate to an empirically derived rainfall rate which was three quarters of the rainfall rate of the area. Two of the predictors developed to identify overestimation will be similar except that one quarter of the rainfall rate of the area used will be added to the area's rainfall rate. For the next predictor, if the variance of the temporal mean rainfall rate was less than a critical value (see Appendix B) or if the variance of any of the scans mean rainfall rate was larger than a critical value (see Appendix B), the rainfall may then have been underestimated. These tests were used to determine whether or not the temporal and spatial homogeneity played a role in identifying the sign of the error.

The DVIP level data was used by the next three predictors of underestimation. For light rain, if the summation of the range bins DVIP levels for all scans of the grid box resulted in only DVIP level one being sampled then an underestimation was possible. Some flexibility was allowed in that a total of five other than DVIP level one range bins could have been totalled while still passing the criteria that only DVIP level one was sampled. For heavy rain, the criteria stated that the summation of all the scan's DVIP levels resulted in only DVIP level one and two range bins being sampled. Similar flexibility was

applied in heavy rain as that for light rain. The reason this predictor was used was that it did not seem possible to have an accurate representation of the DVIP levels if the heavier rain was not accounted for by the sample. This predictor could not be used if only DVIP level one was present in the entire quadrant. For the next two predictors and for light rain, two groups were created consisting of, first, the summation of only DVIP level one, and second, the summation of DVIP levels two through six. The summation was of all range bins of the grid box for all scans. From the small area, the same two groups' range bin were totalled. A chi-square test, using a 95% confidence level, was performed against the grid boxes' first group versus the small areas' first group and against the second group of both the grid box and small area. An underestimation was expected if the grid boxes' first group (DVIP level one) was more than expected or the second group (DVIP level two or greater) was less than expected. A similar comparison was performed using the DVIP levels of the range bins from the large area versus the grid box. For heavy rain, the same chi-square tests were performed except that the first group consisted of DVIP level one and two range bins while the second group was composed of DVIP levels three through six. The results of the two groups and the two areas used for comparison were used as separate predictors for underestimation so four predictors were developed from this process. In order to identify underestimation sixteen predictors were developed from the variables of the grid box, small area, and large area. A summary of the predictors is given in Table 6.

2) Overestimation

The predictors thought to be useful in identifying the overestimation of rainfall will be listed and a summary is provided in Table 7. Most of the predictors are the same used to identify underestimation. The exception called for an overestimation if they failed to identify underestimation.

The first three predictors used the temporally averaged coverage of the grid box by precipitation. In this case, the criteria for the

Table 6. A list of predictors initially used to identify underestimation.

Predictor	Description
1	The temporally averaged coverage of the grid box by precipitation was less than 30%.
2	The temporally averaged coverage of the grid box by precipitation was between 30% and 65%.
3	The temporally averaged coverage of the grid box by precipitation was greater than 65% and less than 90%.
4	The coverage of the grid box by precipitation during the first scan was less than 65%.
5	The variance of the mean rainfall rate of the grid box first scan was less than a critical value (see Appendix B).
6	The temporal mean rainfall rate of the grid box was less than the small area's spatial mean rainfall rate.
7	The temporal mean rainfall rate of the grid box was less than three quarter times the small area's spatial mean rainfall rate.
8	The temporal mean rainfall rate of the grid box was less than the spatial mean rainfall rate of the large area.
9	The temporal mean rainfall rate of the grid box was less than three quarter times the large area's spatial mean rainfall rate.
10	The variance of the temporal mean rainfall rate was less than a critical value (see Appendix B).
11	The variance of the spatial mean rainfall rate of the grid box for all scans was less than a critical value (see Appendix B).
12	For all scans, only DVIP level one precipitation was detected.
13	The chi-square test detected a significant difference between the distribution of group 1 data of the grid box compared to the small area.
14	The chi-square test detected a significant difference between the distribution of group 2 data of the grid box compared to the small area.
15	The chi-square test detected a significant difference between the distribution of group 1 data of the grid box compared to the large area.
16	The chi-square test detected a significant difference between the distribution of group 2 data of the grid box compared to the large area.

Table 7. A list of predictors initially used to identify overestimation.

Predictor	Description
1	The grid box was totally covered by precipitation during at least one scan.
2	The grid box was totally covered by precipitation during more than one but not all scans.
3	The grid box was totally covered by precipitation during all scans.
4	The total number of the grid box DVIP level two range bins was equal to or greater than the number of DVIP level one.
5	The total number of the grid box DVIP level two range bins was equal to or greater than the number of DVIP level one.
6	The variance of the spatial mean rainfall rate for the grid box was larger than a critical value (see Appendix B).
7	The variance of the spatial mean rainfall rate for the grid box was larger than a critical value (see Appendix B) during more than one but not all scans.
8	The variance of the spatial mean rainfall rate for the grid box was larger than a critical value (see Appendix B) during all scans.
9	The temporal mean rainfall rate of the grid box was larger than the spatial mean rainfall rate of the small area.
10	The temporal mean rainfall rate of the grid box was larger than 1.25 times the spatial mean rainfall rate of the small area.
11	The temporal mean rainfall rate of the grid box was larger than the spatial mean rainfall rate of the large area.
12	The temporal mean rainfall rate of the grid box was larger than 1.25 times the spatial mean rainfall rate of the large area.
13	The variance of the mean rainfall rate for the grid box first scan was larger than a critical value (see Appendix B).
14	The chi-square test detected a significant difference between the proportion of the group 1 data of the grid box compared to the small area.
15	The chi-square test detected a significant difference between the proportion of the group 2 data of the grid box compared to the small area.

Table 7. Continued.

Predictor	Description
16	The chi-square test detected a significant difference between the proportion of the group 1 data of the grid box compared to the large area.
17	The chi-square test detected a significant difference between the proportion of the group 2 data of the grid box compared to the large area.
18	The maximum DVIP level observed in the grid box and the small area were the same.
19	The maximum DVIP level observed in the grid box and the large area were the same.

predictors was total coverage by precipitation of the grid box at least once, during more than one but not all scan, as well as all scans. These predictors may indicate whether or not the heaviest portion of the storm was in the grid box at the time the scan was taken.

The next predictor compares the sum of DVIP level two range bins totalled from all scans to the sum of DVIP level one. If this number was equal to or larger than the sum of DVIP level one then an overestimation may occur. Similarly, if the number of DVIP level two or greater range bins was larger than the number of DVIP level one range bins the same result may be expected. One question which may be asked was why make two predictors out of this data when the latter predictor would seem to be sufficient. The reason for this was that the result may have been more favorable in the first case. The second predictor's results would include results from the first so, after the initial application of the predictors to the data base, either one of possibly both predictors will be eliminated.

The twelve predictors which follow are basically the reverse of predictors used in identifying underestimation. First, a) if the variance of the spatial mean rainfall rate was larger than a given value (see Appendix B) for any, b) more than one but not all scans, c) for all scans; second, if the mean rainfall rate of the box was greater

than either the small or larger area, or third, if the variance of the first scan's mean rainfall rate was larger than a critical value (see Appendix B) then an overestimation was indicated. As stated earlier, if the mean rainfall rate of the grid box was larger than 1.25 times the mean rainfall rate of the large or small area then overestimation may have occurred. The chi-square test was once again applied. Except for the case of overestimation, the proportion of the first group must have been less than expected or the second group proportion was more than expected. Finally, the last two predictors which may identify overestimation compare the maximum DVIP level of each grid box to the maximum DVIP level of both the small or large area. The predictor's criteria were satisfied if the two maximums were the same. Two additional requirements were made: first, there must be more than 5 range bins of a given DVIP level in order for that level to be identified as a maximum of the area, and second, neither DVIP level one nor two were allowed to be used as the maximum for either area. This last condition affected the light rain events since there were few range bins of DVIP level three or greater.

Before the results of these two sets of predictors are presented the method by which the results are given will now be discussed. For a given sampling interval, a predictor identifies all grid boxes which satisfy its particular criterion. Then, the number of correct decisions divided by the number of grid boxes identified was calculated. The percentage correct for all sampling intervals was then averaged and displayed in Tables 8 and 9 by category of precipitation and sampling procedure. The results were given in two forms with the first column representing the percent of the grid boxes correctly identified (the Y/N column). The second column which represents the percent correct plus the percent of the incorrect decisions which fell within 5% or no error (10% for heavy rain). The second category was used because improper identification may have been caused by the "noise" of the assumed correct value. Remember, the assumed correct value was the 5-minute sampled data. Fornear's results showed that for a 5-minute sampling interval the error was approximately ± 5% when compared against a one-minute sampling interval. But even with this small

Table 8. The results of the initial set of predictors used to identify underestimation. Values in the Y/N and ± columns are given in percent. Also shown is the percent of the population (POP) each predictor identified as underestimating rainfall.

Predictor	PRECIPITATION											
	Light						Heavy					
	Systematic			Irregular			Systematic			Irregular		
	Y/N	±5	POP	Y/N	±5	POP	Y/N	±5	POP	Y/N	±5	POP
1	90	93	3	89	89	5	76	85	9	81	89	3
2	72	81	29	73	80	26	65	79	31	65	74	27
3	55	69	42	53	62	31	59	74	41	59	71	34
4	72	84	49	67	74	36	68	83	65	64	73	40
5	72	84	45	66	73	35	71	89	56	75	81	28
6	62	74	50	64	75	46	71	83	42	66	77	37
7	66	77	25	80	88	20	77	86	31	72	81	27
8	61	74	63	60	70	68	68	81	59	71	79	62
9	58	71	41	61	72	42	73	85	46	77	85	49
10	60	71	71	54	63	95	80	89	19	75	82	48
11	53	66	50	53	61	73	79	87	21	76	81	33
12	61	72	68	57	66	75	69	80	54	72	80	62
13	26	42	2	75	75	.4	69	92	1	70	84	2
14	40	60	6	59	83	3	67	87	5	52	66	7
15	33	78	.9	33	56	.9	63	94	1	46	54	1
16	56	80	5	39	59	5	73	86	7	50	61	6

amount of error the effect on calculations of error for each grid box could result in shifting any grid box between overestimation and underestimation. The third column represents the number of grid boxes that the predictor correctly identified divided by the total amount of grid boxes in the population. This column was added to show how much of the population the predictor affected. The population size was 948 grid boxes for light and 1351 for heavy rain events. Some caution is

needed in using the third column's data since the number of grid boxes available to the small area was less than the large area. The small area contained 78 and 62 percent of the total population for the light and heavy rain events, respectively.

Table 9. The results of the initial set of predictors used to identify overestimation. Values of the Y/N and ± columns are given in percent. Also shown is the percent of the population (POP) each predictor identified as overestimating rainfall.

	PRECIPITATION											
Predictor	Light						Heavy					
	Systematic			Irregular			Systematic			Irregular		
	Y/N	±5	POP	Y/N	±5	POP	Y/N	±5	POP	Y/N	±5	POP
1	52	70	61	54	66	51	44	62	58	46	58	64
2	57	73	41	58	85	41	45	64	39	47	57	44
3	73	92	8	63	73	16	61	66	6	54	58	14
4	100	100	.5	100	100	.1	63	77	5	65	82	8
5	100	100	.5	100	100	.1	64	81	14	65	75	16
6	42	57	50	45	55	30	45	62	79	50	61	69
7	52	64	4	43	51	4	54	66	22	52	60	26
8	89	89	.9	57	57	2	68	70	8	57	62	17
9	61	72	27	61	69	32	51	75	25	59	70	32
10	77	85	10	73	80	16	55	78	16	56	68	24
11	54	67	37	59	67	35	51	72	41	61	72	40
12	56	70	24	61	69	23	59	81	30	67	79	30
13	59	73	55	53	63	68	54	69	44	48	59	72
14	83	92	4	73	88	3	81	100	1	75	90	3
15	76	85	8	67	80	10	58	86	10	66	82	8
16	73	86	7	58	75	6	69	90	10	79	89	9
17	67	79	16	60	70	15	60	82	20	68	80	19
18	63	81	6	56	77	3	57	81	19	71	83	15
19	63	83	6	63	75	3	50	72	32	61	74	30

Table 8 presents the results of each predictor used to identify underestimation. The first three predictors concerned temporal area coverage. As the coverage decreased the tendency to underestimate rainfall increased. Of the three, Predictors 1 and 2 did well. Predictor 1 was only applicable against a small portion of the population while Predictor 2 attacked a larger portion of the population but did not do as well identifying underestimation. So, these two predictors were combined to include slightly more of the population. The criteria for the new predictor will be temporal area coverage by precipitation of the grid box of less than 75%. Predictors 4 and 5 concerned spatial area coverage by precipitation and homogeneity, respectively, of the first scan. Both had similar results in light rain but Predictor 5 was superior in heavy rain. Heavy rain tends to be nonhomogeneous and it is logical that this predictor would perform well. The predictors which used the mean rainfall rate of the small and large area, 6 and 8, were not outstanding but did show a little improvement over just a guess. The two other predictors, 7 and 9, which used only three quarters of the mean rainfall rates fared better. What was wanted from Predictors 7 and 9 was an improvement over Predictors 6 and 8 while still addressing a significant portion of the population. Similarly, Predictor 7 did better than Predictor 6 in all categories of precipitation but it's population loss was large. But the improvement seemed to override the population concern so Predictor 7 will be used for both categories of precipitation. Comparing Predictors 8 and 9, which used the large area mean rainfall rate, the improvement and population criteria mentioned above were met by Predictor 9 in heavy but not light rain. So this predictor will be used in lieu of Predictor 8 for heavy rain. Because of the variance of the temporal mean rainfall rate, Predictor 10 worked well in heavy rain. It also shows clearly the effect of not having the first scan since, in the irregular sampling procedure, it was of significantly less help than in the systematic procedure. Predictor 11, which concerned the variance of the spatial mean rainfall rate, did not work well in light rain but in heavy rain the results were much better. Predictor 12 seems to work fairly well against all categories of precipitation but was a little

better in the systematic sampling procedure. All of the chi-square predictors were disappointing since they identified only a small percentage of the population and the results were unfavorable. For these reasons, they will not be used as predictors in the reduced set.

Table 9 displays the results of the predictors used to identify overestimation. The first three predictors were concerned with the number of scans in which the grid box was totally covered by precipitation. Improvement in identification of overestimation was exhibited by all three predictors but more so in the light rather than the heavy rain category. Predictor 3 provided the best results but was only applicable to a small portion of the population. Predictors 2 and 3 were combined and used in the reduced set of predictors. Predictor 1 had very similar results to 2 in heavy rain but did about 5% less in light rain. The next two predictors were an intercomparison of the DVIP levels of the grid box. These predictors worked well in heavy rain. As stated before, what difference does it make whether or not the summation of DVIP level one range bins was compared against just DVIP (Predictor 4) level two or all other DVIP levels (Predictor 5). Both did fairly well identifying overestimation but the population factor was in favor of the latter. The reduced set will contain only Predictor 5 but, in application, Predictor 4 would probably perform the same except for the smaller population results. The next three predictors were concerned with the variance of the mean rainfall rate of the grid box. Performance of these predictors was poor in light rain but in the heavy rain events, as the number of scans with a large variance increased, the likelihood of overestimating increased. These three predictors were combined into one with the new criteria being the occurrence of a large variance in more than one scan. The next two predictors, 9 and 10, used the small area mean rainfall rate and 1.25 times the mean rainfall rate as criteria. The results were very similar to their performance as indicators of underestimation. Predictor 9 was used in the reduced set for heavy rain due to similar results in identification of overestimation and because of the larger population it addressed. Predictor 10 will be used in light rain due to the excellent results it obtained. The comparison with the percentage of

the population each predictor affected does not take into account the skewness of the data base. From Table 9, Predictor 10 identified 10% of the population for light rain systematically sampled as an overestimation. From Table 4, only 45% of the grid boxes of the population were overestimated. This means the Predictor 10 identified 17% of the grid boxes which actually had overestimated rainfall. Also, taking into account that the small area method had only 78% of the population available, this predictor actually identified an even higher percentage of grid boxes in which the rainfall was overestimated. Predictors 11 and 12 were basically the same predictors and 9 and 10 but they used the large area mean rainfall rate. Unlike the small area, Predictor 10 did well in light rain but Predictor 12 worked best in heavy rain. This may indicate that, in heavy rain when an overestimation occurs, the sampled mean rainfall rate of the grid box was well above that of the entire area. One may suspect that, when this occurs, the sample was taken when the storm was at or near peak intensity in the grid box. Predictor 13 used the variance of the mean rainfall rate of the first scan as criteria. The predictor appeared to do better with the systematic rather than irregular sampling procedure. The next four predictors were the chi-square comparisons between the grid box DVIP levels and either the small or large area DVIP levels. All predictors performed well except that the percentage of the population was somewhat low. In the reduced set of predictors, the two chi-square tests for each area used was combined such that a grid box was identified as overestimating rainfall if the chi-square test detected a significant difference in either group's proportion. This action was taken to increase the percentage of population identified as overestimating precipitation. The last two predictors, 18 and 19, compared the maximum DVIP level sampled in the grid box to that of either the large or small area. In light rain, neither predictor identified a large portion of the population as overestimating total rainfall. This was mainly a result of there being only a few range lines with greater than DVIP level two. Added to the reduced set of predictors for overestimation will be the temporally averaged coverage by precipitation of the grid box and the first scan coverage by precipitation. Both these

predictors are identically opposite of the predictors used for underestimation. Summaries of the reduced set of predictors used to identify underestimation and overestimation are presented in Tables 10 and 11.

c. The reduced set of predictors

Tables 10 and 11 list the new or redefined predictors as well as the original predictors which were not changed. The results for the new and redefined predictors will be given in the sections to follow.

Table 10. The reduced list of predictors used to identify underestimation.

Predictor	Description
A	The temporally averaged coverage of the grid box by precipitation was less than 75%.
B	The grid box first scan coverage by precipitation was less than 75%.
C	The variance of mean rainfall rate of the grid box first scan was less than a critical value (see Appendix B).
D	The temporal mean rainfall rate of the grid box was less than the small area's spatial mean rainfall rate.
E	The temporal mean rainfall rate of the grid box was less than the three quarter times the small area's spatial mean rainfall rate.
F	The temporal mean rainfall rate of the grid box was less than the spatial mean rainfall rate of the large area.
G	The temporal mean rainfall rate of the grid box was less than the three quarter times the large area's spatial mean rainfall rate.
H	The variance of the temporal mean rainfall rate was less than a critical value (see Appendix B).
I	For all scans, the variance of the spatial mean rainfall rate of the grid box was less than a critical value (see Appendix B).
J	For all scans, only DVIP level one precipitation was detected.

Table 11. The reduced list of predictors used to identify overestimation.

Predictor	Description
A	The grid box was totally covered by precipitation during more than half of the scans.
B	The total number of the grid box DVIP level two or greater range bins was equal to or greater than the number of DVIP level one.
C	The variance of the spatial mean rainfall rate for the grid box was larger than a critical value (see Appendix B).
D	The temporal mean rainfall rate of the grid box was larger than the spatial mean rainfall rate of the small area.
E	The temporal mean rainfall rate of the grid box was larger than 1.25 times the spatial mean rainfall rate of the small area.
F	The temporal mean rainfall rate of the grid box was larger than the spatial mean rainfall rate of the large area.
G	The temporal mean rainfall rate of the grid box was larger than 1.25 times the spatial mean rainfall rate of the large area.
H	The variance of the mean rainfall rate of the grid box first scan was larger than a critical value (see Appendix B).
I	The temporally averaged area coverage by precipitation for the grid box was greater than or equal to 75%.
J	The coverage by precipitation of the grid box first scan was greater than or equal to 75%.
K	The chi-square test detected a significant difference between the proportion of either group 1 or group 2 data of the grid box compared to the small area.
L	The chi-square test detects a significant difference between the proportion of either group 1 or group 2 data of the grid box compared to the large area.
M	The maximum DVIP level observed in the grid box and the small area was the same.
N	The maximum DVIP level observed in the grid box and the large area was the same.

d. Results

Now that the reduced set of predictors has been formed for both over and underestimation the next step will be to present the results of these predictors when used in combination with one another. Results in this section are those which are an average of the sampling intervals while results for the individual sampling intervals are presented in Appendix A. Since some of the predictors were new or redefined the new results will be given here. In addition, graphical results of several predictors using the individual sampling interval results are presented in Appendix B.

1) Underestimation

a) Light rain

Table 12 lists six predictors from the reduced set which appeared useful in identifying underestimation of light rain events. The same set of predictors will be used for both the systematic as well as the irregular sampling procedure. Most of the six predictors showed a gain over "persistence" of as little 6% to as much as 25%. Persistence is defined as the distribution of error, both over or underestimation, of the data base developed for this research. The best result was by Predictor E. The loss of the first scan allowed Predictor E to perform better in the irregular procedure. Since the systematic procedure did not work as well for Predictor E the first scan must have a rainfall rate larger than the mean rainfall rate of the grid box to pull the grid box mean rainfall rate to within 25% of the small area's mean rainfall rate. With Predictor E as the exception, the tendency was for the results to be slightly better in the systematic instead of the irregular sampling procedure. This was true for both categories of precipitation as well as in over and underestimation.

The results for the combinations of the six predictors is presented in Table 13. Not surprising was the outstanding results attained by combinations which included Predictor E. This predictor performed best

Table 12. A list and results of the predictors which were used to identify underestimation in light rain events.

Predictor	SAMPLING			PROCEDURE		
	Systematic			Irregular		
	Y/N	±5	POP	Y/N	±5	POP
A	72	82	47	72	78	41
B	72	84	49	67	74	36
C	72	84	45	66	73	35
E	66	77	25	80	88	20
F	61	74	63	60	70	68
J	61	72	68	57	66	75

in the systematic procedure when used in combination with Predictor C, the variance of the first scan mean rainfall rate. So, for a homogeneous first scan combined with a mean rainfall rate 25% less than the small area, a high percentage of the grid boxes which met this criteria were underestimated. Other pairs of predictors which performed well were A and B, A and C, and C and F. Predictor F showed improvement with all predictors and worked well with a large portion of the population. Predictor J seems to be the weakest of all at this point.

Table 14 shows the results resulting from the use of three predictors. Only the combinations which showed improvement over the paired predictors are listed. The improvement was generally only a few percentage points with a resultant drop in the percent of the population identified as underestimated. It was interesting to note that Predictor J, which had previously performed poorly, actually provided the extra help for four of the nine "triplets." The most noticeable gain associated with Predictor J was with Predictors A and E where 12 percent of the population was identified as overestimating a rainfall with a 90% success rate.

Table 13. The results of predictors used in combination with one another in order to identify underestimation of light rain events.

Predictor	SAMPLING			PROCEDURE		
	Systematic			Irregular		
	Y/N	±5	POP	Y/N	±5	POP
A with						
B	76	85	36	70	76	32
C	77	87	33	74	77	25
E	79	83	14	90	96	12
F	72	82	35	72	83	32
J	74	83	40	73	79	37
B with						
C	73	85	43	68	74	27
E	82	90	14	90	94	11
F	72	84	49	67	74	36
J	75	86	40	69	76	33
C with						
E	85	95	12	89	95	12
F	75	87	35	73	78	30
J	76	86	37	69	75	29
E with						
F	68	77	23	79	88	19
J	69	78	22	81	87	18
F with						
J	62	73	56	61	71	60

Table 14. The results of the three way combinations of predictors used to identify underestimation of light rain events. Only triplets of predictors which showed improvement over the paired predictors are shown.

Predictor	SAMPLING			PROCEDURE		
	Systematic			Irregular		
	Y/N	±5	POP	Y/N	±5	POP
A and C with						
F	79	90	26			
J	78	88	29			
A and E with						
B	88	91	10	91	95	10
C	85	94	11			
J	90	96	12	90	96	12
F and C with						
B				78	83	23
E and J with						
C				90	93	9

where 12 percent of the population was identified as overestimating rainfall with a 90% success rate.

b) Heavy rain

Eight predictors were to identify underestimation of heavy rainfall with results given in Table 15. The predictors which worked with the variance of the rainfall rates, C, H, and I, had the best initial results. This was anticipated since non-homogeneity was an expected occurrence during heavy rainfall. Also, the range of results between predictors was large compared to the light rain events.

Table 15. A list of the predictors which were used to identify underestimation in heavy rain events.

Predictor	SAMPLING PROCEDURE					
	Systematic			Irregular		
	Y/N	±10	POP	Y/N	±10	POP
A	64	78	54	66	76	46
B	68	83	65	64	73	40
C	71	89	56	75	81	28
E	77	86	31	72	81	27
G	73	85	46	77	85	49
H	80	89	19	75	82	48
I	79	87	21	76	81	33
J	69	80	54	72	80	62

Table 16 shows the results of the variables used in combination with one another. Once again, Predictor E obtained the best results. It worked particularly well with Predictors B and C. Predictor H, which had the best initial results, showed some improvement but not with all predictors. For the irregular sampling procedure, Predictor I, working with the variance of the mean rainfall rate for all scans, seemed to work best although predictors G and C also performed well. Using the systematic procedure for both light and heavy rain showed that the mean rainfall rate of the small area was a better predictor than the mean rainfall rate of the large area. But, using the irregular procedure in heavy rainfall showed that the mean rainfall rate for the large area was best. The large area mean rainfall rate should have been a better prediction than the mean of the small area. It is not known why there was a sudden difference in the performance of the two predictors.

Table 16. The results of predictors used in combination with one another to identify underestimation of heavy rain events.

Predictor	SAMPLING			PROCEDURE		
	Systematic			Irregular		
	Y/N	±10	POP	Y/N	±10	POP
A with						
B	69	83	47	66	74	36
C	73	85	39	77	82	23
E	82	89	20	75	84	15
G	76	88	32	81	88	30
H	80	89	17	74	82	33
I	84	91	12	82	87	18
J	68	81	42	72	80	39
B with						
C	71	86	51	75	81	24
E	85	91	21	73	81	14
G	78	91	35	79	85	26
H	82	91	17	73	80	29
I	81	91	16	80	85	19
J	73	86	41	70	76	34
C with						
E	85	91	19	76	83	9
G	78	90	33	82	87	23
H	82	90	17	79	85	23
I	81	92	16	82	87	17
J	76	86	37	79	85	24
E with						
G	77	86	23	77	83	21
H	85	89	10	78	85	17
I	87	91	10	80	84	13
J	79	86	14	77	69	15

Table 16. Continued.

Predictor	SAMPLING			PROCEDURE		
	Systematic			Irregular		
	Y/N	±10	POP	Y/N	±10	POP
G with						
H	80	89	19	81	87	29
I	83	90	16	83	87	27
J	74	85	39	81	87	44
H with						
I	82	88	11	83	87	26
J	80	89	19	76	82	47
I with						
J	84	90	15	82	87	27

Three-way combinations of predictors used to identify underestimation with improved accuracy over paired sets are shown in Table 17. Although improvements was noted in both procedures only three triplets showed improvement for the irregular procedure. Ten of the eleven sets of predictors had at least one predictor which used variance as criteria. It was difficult for any combination of predictors to identify correctly either over or underestimation with an accuracy greater than 90%. This may be attributable to the diversity of the data base created from the six rain events. Use of these results in other applications will probably produce similar results.

Before proceeding with an explanation regarding prediction, confidence intervals associated with the results will be discussed. For a binomial distribution, a 90% confidence interval is of the form:

$$\hat{\Pi} \pm 1.96 \sqrt{\frac{\hat{\Pi}\ (1-\hat{\Pi})}{N}}$$

where $\hat{\Pi}$ is the number of correct guesses divided by the sample size, N

Table 17. The results of the three way combinations of predictors used to identify underestimation of light rain events. Only triplets of predictors which showed improvement over the paired predictors are shown.

Predictor	SAMPLING			PROCEDURE		
	Systematic			Irregular		
	Y/N	±10	POP	Y/N	±10	POP
A and C with						
I	86	93	11			
J	78	88	29			
E and J with						
B	87	93	17			
I	87	89	8	86	88	11
E and A with						
B	86	92	17			
B and J with						
I	86	92	12			
G and C with						
E	84	92	15			
I and J with						
C	87	93	12			
I and J with						
G				85	89	26
G and C with						
I				84	89	16

(Ott, 1984). It can be shown for virtually all of the single, paired, or triple combination of predictors that their respective confidence interval does not contain the population mean. But, this does not mean that the single predictor results were not part of the confidence interval of the predictors used in pairs or triplets. Although improvement was noted when combinations of predictors were applied to the

data base, a resulting decrease in sample size prevented one from being able to state that statistically the improvement was significantly different than that of either single predictor. Also, for the results given in Appendix A for predictors according to sampling interval, the problem of not being able to show statistical improvement for combinations of predictors still remains. However, in this situation even some paired and triple combinations of predictors have a confidence interval that encloses the population mean. With more data it is believed that the results would not change and that the trend for increased accuracy with more than one predictor would continue.

2) Overestimation

a) Light rain

Eight predictors from the reduced set showed applicability in predicting overestimation of light rain. Table 18 lists the results of these predictors. The results can be classified in two ways: good results with low population or mediocre results with high population. Discounting the ± 5 category, the predictors used to identify underestimation performed better as the sampling interval increased.

For overestimation some predictors followed this pattern while others performed better with the shorter sampling intervals. This was not an expected result since it was thought to be harder for a predictor to do well in the shorter sampling intervals. The problem of low population totals was even more pronounced. Several individual predictors would capture less than 10% of the population. This was expected in the case of Predictor E since only 45% of the population of light rain events were overestimated and use of th small area lessened the number of grid boxes available to the predictor by about 25%. It is not known if the distribution of error for over versus underestimation remained the same for the small area compared to the large area. Assuming a similar distribution, the 10% of the population identified by Predictor E using the systematic procedure was closer to underestimation remained the same for the small area compared to the

Table 18. A list of the predictors which were used to identify overestimation in light rain events.

Predictor	SAMPLING PROCEDURE					
	Systematic			Irregular		
	Y/N	±5	POP	Y/N	±5	POP
A	57	74	41	58	70	43
E	77	85	10	73	80	16
F	54	67	37	59	67	35
H	59	73	55	53	63	68
I	61	76	51	54	65	67
J	60	76	52	57	78	61
K	76	85	8	67	80	10
L	67	79	16	60	70	15

large area. Assuming a similar distribution, the 10% of the population identified by Predictor E using the systematic procedure was closer to 13% of the population. Of this, 77% of the grid boxes were correctly identified as overestimated. So, Predictor E actually identified 22% of the grid boxes which had overestimated rainfall. Now it can be seen that some of the predictors with the lower population totals performed better than the table indicates. The best individual Predictors, E, K, and L, were the mean rainfall rate of the small area and the two chi-square tests. The reason the chi-square tests worked well may be that the test was identifying situations wherein the sample contained a scan of the storms during peak intensity. When the ± 5 factor was included the percent correct was even better for the chi-square tests. This may be due to the fact that sampling the storm at its peak was counterbalanced by the other scans with lower mean rainfall rates. The results were overestimations or close to overestimations of the rainfall.

Table 19 shows the results of combinations of predictors used to identify overestimation of light rain. Two striking results were apparent. First, for most combinations the results are far better when using the systematic rather than the irregular sampling procedure. Second, the best predictor to use in combination with another was once again Predictor E. Predictor E, as in other situations, affected a very small percentage of the population. Again, predictors which affected a large portion of the population did not ring up impressive results. Finally, the percentage of the population affected was larger for the irregular vice systematic procedure. This may have been due to the missing first scan. If this was true, then in application of the irregular procedure the results should fall somewhere between the results of the two sampling procedures because the irregular sampling procedure was a worst case scenario. In practice, the first scan used by the systematic procedure may also be the first scan used by the irregular procedure. In retrospect, results of the irregular sampling procedure should be thought of as a worse case situation rather than what would occur in actual application.

Predictor E was not used in the three way combination of predictors in the systematic procedure since the portion of the population it affected was too low. Table 20 shows the results of the predictors used in three way combinations. For the systematic procedure, only slight improvement was realized. When using the irregular procedure the best results were obtained from the predictors which used the mean rainfall rate of the small area, the variance of the first scan, and the temporally averaged coverage of the grid box by precipitation. Since the irregular procedure did not produce results as good as the systematic procedure, the additional predictor allowed more improvement that that shown in the systematic procedure.

b) Heavy rain

The results for the predictors used to identify overestimation of heavy rain events are shown in Table 21. The best predictors were the

Table 19. The results of predictors used in combination with one another to identify overestimation of light rain events.

Predictor	SAMPLING PROCEDURE					
	Systematic			Irregular		
	Y/N	±5	POP	Y/N	±5	POP
A with						
E	84	86	6	82	89	9
F	64	75	19	65	75	18
H	66	81	30	58	71	38
I	62	78	35	60	72	40
J	66	82	30	58	70	40
K	76	83	6	69	84	7
L	72	85	10	59	72	10
E with						
F	76	82	8	74	80	14
H	82	86	8	75	81	15
I	89	90	8	82	87	12
J	82	86	8	75	81	13
K	82	86	5	75	82	12
L	81	85	7	77	82	7
F with						
H	61	72	27	58	66	29
I	67	77	25	64	72	12
J	62	73	25	60	69	27
K	76	85	8	69	78	9
L	67	89	16	60	74	15
H with						
I	66	80	41	60	70	53
J	62	77	49	55	66	60
K	76	84	7	68	79	9
L	69	81	14	61	70	15

Table 19. Continued.

Predictor	SAMPLING			PROCEDURE		
	Systematic			Irregular		
	Y/N	±5	POP	Y/N	±5	POP
I with						
J	66	81	40	58	70	57
K	81	86	6	71	86	8
L	74	85	13	63	75	13
J with						
K	76	84	7	67	80	9
L	68	81	14	60	71	14
K with						
L	76	85	8	68	77	9

chi-square tests, the maximum DVIP level comparisons, and the situations in which the total of DVIP level three or greater range bins exceeded the total of the DVIP level one and two range bins. Twelve predictors were retained because only a few actually performed well and it was thought the other predictors may work better when used in combination with other predictors.

The results of combinations of the 12 predictors used to identify overestimation of heavy rain events are presented in Table 22. The differences between the Y/N category and the ± 10% categories are interesting since the results of the latter category approached 90% while the former was markedly less. This was the greatest difference for all sets of predictors. The reason for this may be that, for heavy rain, an unrepresentative sample does not always result in overestimation. This is due to the fact that the various combinations of rainfall rates sampled may average out to be correct more by accident than

Table 20. The results of the three way combinations of predictors used to identify underestimation of light rain events. Only triplets of predictors which showed improvement over the paired predictors are shown.

Predictor	SAMPLING Systematic			PROCEDURE Irregular		
	Y/N	±5	POP	Y/N	±5	POP
A and I with						
L	74	85	10			
I and J with						
F	68	78	21			
H	68	82	38			
I and L with						
H	68	81	14			
E and J with						
H				77	82	13
K				75	83	6
L				79	85	8
E and H with						
I				83	88	11
L				78	84	9
H and J with						
E				77	82	13
H				68	82	38

by having a reasonable sample. The predictors which worked well singly continued to perform well in combination with other predictors.

Finally, Table 23 presents the results of 3-way combinations of predictors used to identify overestimation of heavy rain events. As in all other cases, the slight amount of improvement was made at the expense of the number of grid boxes identified as overestimating

Table 21. A list of the predictors which were used to identify overestimation in heavy rain events.

Predictor	SAMPLING PROCEDURE					
	Systematic			Irregular		
	Y/N	±10	POP	Y/N	±10	POP
A	45	64	39	47	57	44
B	64	81	14	65	75	16
C	45	66	38	44	59	27
D	51	75	25	59	70	32
G	59	81	30	67	79	30
H	54	69	44	48	59	72
I	55	67	35	45	56	62
J	45	64	46	48	59	55
K	58	86	10	66	82	8
L	60	82	20	68	80	19
M	57	81	19	71	83	16
N	50	72	32	61	74	30

precipitation. The improvements were more in the Y/N category rather than the ± 10% category. So, these combinations of predictors eliminated grid boxes with error above and below the 10% line. The best results involved combinations of Predictors B, H, and M. So, as before, the variance or homogeneity was a helpful indicator of overestimation.

Table 22. The results of predictors used in combination with one another to identify overestimation of heavy rain events.

Predictor	SAMPLING PROCEDURE					
	Systematic			Irregular		
	Y/N	±10	POP	Y/N	±10	POP
A with						
B	63	81	12	63	74	15
C	48	73	12	34	47	10
D	47	78	13	61	70	16
G	61	85	16	67	77	20
H	53	69	24	48	52	42
I	46	65	35	50	60	40
J	53	66	23	47	57	42
K	57	88	7	69	82	6
L	59	84	15	69	80	15
M	69	87	11	71	83	10
N	49	73	16	63	74	17
B with						
C	66	85	5	46	61	5
D	67	89	6	67	79	7
G	68	87	12	73	83	13
H	71	85	10	66	76	15
I	61	81	11	68	78	14
J	70	83	8	65	75	15
K	70	92	4	70	87	4
L	69	88	11	73	84	11
M	69	88	8	78	88	6
N	69	91	5	67	79	8

Table 22. Continued.

Predictor	SAMPLING			PROCEDURE		
	Systematic			Irregular		
	Y/N	±10	POP	Y/N	±10	POP
C with						
D	52	77	10	45	64	10
G	58	81	14	57	73	11
H	57	76	22	46	59	22
I	47	72	14	39	56	11
J	59	74	15	38	52	16
K	66	89	3	41	75	2
L	58	82	8	53	70	7
M	50	78	8	58	70	7
N	48	73	14	47	66	11
D with						
G	51	75	25	59	70	30
H	57	79	13	60	70	28
I	43	73	16	61	72	22
J	55	74	9	57	68	24
K	59	87	10	66	82	8
L	53	77	21	60	75	22
M	57	86	10	69	81	10
N	53	77	21	60	74	22
G with						
H	64	81	19	67	78	28
I	57	82	20	66	78	24
J	66	81	16	65	77	25
K	63	92	7	66	83	6
L	63	86	18	70	81	18
M	63	87	15	72	84	13
N	57	84	17	65	79	17

Table 22. Continued.

Predictor	SAMPLING PROCEDURE					
	Systematic			Irregular		
	Y/N	±10	POP	Y/N	±10	POP
H with						
I	51	68	30	50	60	51
J	58	71	31	46	57	59
K	64	89	5	68	82	8
L	66	85	12	70	80	19
M	66	86	11	70	82	15
N	57	78	17	61	74	27
I with						
J	51	64	28	48	58	51
K	53	86	8	68	84	7
L	58	83	16	67	79	16
M	58	86	13	71	84	12
N	46	72	21	62	75	23
J with						
K	75	94	4	68	82	7
L	67	85	11	69	79	15
M	68	85	9	72	82	13
N	55	71	13	59	72	24
K with						
L	64	91	7	66	82	6
M	62	92	6	71	85	4
N	62	87	9	65	81	8
L with						
M	64	86	13	68	80	10
N	54	80	12	65	79	12
M with						
N	60	81	14	71	82	12

Table 23. The results of three way combinations of predictors used to identify overestimation of heavy rain events. Only triplets of predictors showing improvement over the paired predictors are shown.

Predictor	SAMPLING			PROCEDURE		
	Systematic			Irregular		
	Y/N	±10	POP	Y/N	±10	POP
B and G with						
D	69	92	5	73	86	7
H	73	88	8			
L	70	89	11	75	86	10
N	70	90	5			
B and H with						
C	72	88	6			
L	74	89	8	76	85	10
M	74	89	6	79	85	10
N	75	91	4			
G and L with						
H	67	86	12			
K	63	91	7			
B and G with						
M				89	87	6
D and J with						
L				67	80	11
G and I with						
M				72	82	10

4. SUMMARY AND CONCLUSIONS

The purpose of this study was to develop a set of predictors which could identify either over or underestimation of radar derived rainfall. Four sets of predictors were developed for application to conditions of light or heavy rainfall. The results were presented, for both types of sampling procedures.

There was a significant difference in the distribution of error of light and heavy rain events but no such difference was apparent between sampling procedures. The heavy rain events were underestimated more than the light rain events by about 5%. Predictors developed to identify the sign of the error were applicable to both procedures. The results presented for the irregular procedure represented a worst case scenario since the first scan was not used in this procedure for rainfall estimation.

Six predictors were used to identify underestimation of light rain events. The best predictors used the mean rainfall rate, temporal coverage by precipitation of the grid box, and the variance of the mean rainfall rate of the first scan. These results were the best of the four sets of predictors with a 90% success rate when using more than one predictor.

For identification of underestimation of heavy rain events, the mean rainfall rate and both the spatial and temporal variance of the mean rainfall rate worked well. Results approached 90% for several combinations of predictors. For three way combinations that showed improvement, the variance of the mean rainfall rate was utilized in ten of the eleven combinations. Predictors of underestimation performed better as the sampling interval increased. Generally, predictors used to identify underestimation performed better than those used for overestimation.

Eight predictors were developed for identification of overestimation of light rain events. The best performance was, once again, made by the use of the mean rainfall rate but the chi-square tests also performed well. A success rate of nearly 85% was accomplished by several combinations of predictors.

Finally, twelve predictors were used to identify overestimation of heavy rain events. The best performances were obtained by the predictors which utilized the DVIP levels. These predictors were the chi-square test, maximum DVIP level, and the number of DVIP level 3 or greater range bins that are greater than the DVIP level 2 or less range bins. Twelve predictors were required because of the poor initial results. These predictors exhibited the widest margin between the Y/N and the ± categories. The success rate approached 80% for various combinations of predictors. Unlike predictors used to identify underestimation, some predictors performed better in the smaller sampling intervals.

Many studies have been undertaken to compare radar derived rainfall to rain gage data. It would be interesting to determine whether the predictors used here agree with the sign of the error obtained from radar-rain gage comparison.

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APPENDIX A

The following pages contain the results of the reduced set of predictors for both over and underestimation according to sampling interval. The sampling intervals used were 10, 15, 20, 30, 40, and 50 minutes. This is given in the same order of results presented in Tables 12 through 23.

Predictor	UNDERESTIMATION — Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
LIGHT RAIN												
	Y/N						±5					
Systematic Procedure												
A	67	71	75	70	74	92	82	79	84	77	76	92
B	68	79	73	74	76	84	86	89	88	81	78	88
C	64	76	72	73	77	82	85	85	87	82	79	85
E	62	63	68	70	62	72	80	73	79	81	66	83
F	57	66	56	63	58	66	76	76	73	78	61	74
J	55	66	60	61	59	68	74	74	74	72	63	76
Irregular Procedure												
A	59	70	67	83	91	97	66	78	74	90	91	97
B	55	70	76	87	91	100	66	76	80	94	91	100
C	53	64	71	74	74	81	62	72	75	78	88	84
E	79	74	73	86	91	95	84	80	84	86	93	95
F	56	56	50	68	66	72	66	71	63	72	78	78
J	50	54	48	68	64	71	60	65	57	71	77	78
HEAVY RAIN												
	Y/N						±10					
Systematic Procedure												
A	64	59	60	61	72	76	88	77	72	73	77	78
B	70	65	69	66	72	75	91	85	82	78	83	80
C	73	66	67	69	75	80	91	88	80	80	87	85
E	76	74	66	79	84	85	93	89	79	82	91	85
G	64	64	68	79	87	90	85	82	80	84	91	90
H	69	74	78	81	94	97	90	89	80	83	94	97
I	75	75	73	78	93	85	89	91	78	81	98	90
J	64	61	62	72	79	78	87	79	74	79	85	78
Irregular Procedure												
A	57	61	69	66	77	86	71	72	76	76	82	88
B	55	59	65	68	85	87	67	69	73	75	87	91
C	61	68	80	77	90	94	69	76	84	82	90	97
E	57	64	84	75	74	83	73	75	88	85	81	88
G	65	69	77	87	84	94	77	81	82	90	86	94
H	59	66	76	79	85	93	73	75	82	85	89	93
I	61	65	76	80	80	93	75	76	80	82	81	93
J	63	64	73	74	78	82	76	73	78	82	82	83

Predictor	UNDERESTIMATION											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
LIGHT RAIN												
	Y/N						±5					
	Systematic Procedure											
A with												
B	68	75	79	71	79	96	83	84	88	78	82	96
C	69	76	82	72	79	96	86	86	92	79	82	96
E	66	76	83	85	93	83	76	76	86	91	85	93
B with												
E	70	86	89	82	88	89	87	86	88	95	88	100
J	65	78	75	78	78	91	83	85	88	88	83	91
C with												
E	72	88	83	86	93	92	94	88	93	100	93	100
F	67	80	72	80	76	85	88	88	89	91	78	85
J	64	78	78	80	81	87	84	85	91	89	83	88
F with												
J	58	67	57	63	58	68	76	75	72	76	61	75
	Irregular Procedure											
A with												
C	59	75	70	86	90	91	67	79	74	91	90	91
E	83	85	90	100	100	100	90	96	95	100	100	100
F	66	78	68	84	92	97	76	88	74	89	92	97
J	60	72	67	83	93	94	76	88	74	89	92	97
B with												
E	81	87	89	100	100	100	85	96	95	100	100	100
J	54	66	65	85	86	93	62	72	75	78	88	84
C with												
E	82	83	95	93	100	100	86	96	95	93	100	100
F	61	74	70	77	82	88	71	80	72	80	93	88
J	56	66	70	79	79	82	65	72	74	84	93	86
E with												
F	78	74	72	85	81	95	84	90	83	85	93	95
HEAVY RAIN												
	Y/N						±10					
	Systematic Procedure											
A with												
E	78	78	74	80	92	95	93	90	79	84	94	95
G	66	66	71	81	95	100	89	83	82	88	95	100
I	73	77	78	88	100	95	85	92	85	91	100	100

Predictor	UNDERESTIMATION											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
HEAVY RAIN (Continued)												
	Y/N						±10					
Systematic Procedure (Continued)												
B with												
C	73	68	68	68	74	81	92	90	82	79	86	86
G	70	71	74	84	89	96	91	90	86	90	93	96
H	72	77	84	85	93	96	91	93	86	87	93	96
I	79	73	82	79	87	88	88	95	89	83	97	94
J	70	66	70	74	83	85	92	85	80	83	87	85
C with												
E	86	93	74	86	91	90	97	96	82	89	97	90
G	71	69	70	85	93	94	94	90	83	89	98	94
H	70	74	81	85	97	96	91	90	84	85	97	96
I	79	73	79	81	90	88	88	95	88	86	100	94
J	72	68	68	81	89	88	90	87	80	86	93	88
E with												
H	81	78	78	83	100	95	92	87	78	83	100	95
I	83	89	71	90	100	89	91	94	81	90	100	89
G with												
I	76	75	74	83	94	92	86	94	84	85	87	93
H with												
I	70	75	77	85	95	95	83	92	82	85	95	95
I with												
J	74	81	76	86	97	92	85	94	83	88	97	92
Irregular Procedure												
A with												
C	60	71	78	84	90	96	68	80	83	87	90	100
E	52	68	89	81	91	100	71	77	95	87	96	100
G	64	76	80	93	96	100	77	88	86	98	96	100
I	64	80	76	91	89	96	76	90	80	93	89	96
B with												
E	49	63	89	74	94	100	65	72	95	84	94	100
G	63	71	79	93	95	100	72	82	84	96	95	100
I	63	70	75	89	87	96	72	81	78	91	87	96
C with												
G	64	77	86	95	95	97	74	85	89	98	95	97
H	62	74	88	84	91	100	71	83	85	88	91	100
I	61	77	78	87	87	96	73	85	83	90	87	96

Predictor	UNDERESTIMATION											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
HEAVY RAIN (Continued)												
	Y/N						±10					
	Irregular Procedure (Continued)											
E with												
H	57	65	89	87	94	96	72	75	93	90	94	96
I	67	75	86	84	76	91	70	88	86	87	80	91
G with												
H	62	73	83	91	89	97	77	83	87	94	91	97
I	62	76	82	91	89	96	75	86	85	92	89	96
J	66	73	81	90	87	86	80	83	85	94	88	96
H with												
I	62	80	78	90	89	96	80	83	85	94	88	96
I with												
J	64	78	78	90	86	97	77	87	82	91	86	87
LIGHT RAIN												
	Y/N						±5					
	Systematic Procedure											
A and C with												
F	68	78	82	83	77	95	88	89	92	92	82	95
J	69	79	82	80	78	96	86	87	93	88	81	96
A and E with												
B	78	94	86	86	92	100	83	94	91	93	92	100
C	67	88	82	85	93	100	93	88	93	100	93	100
J	65	78	85	85	92	100	77	78	89	95	92	100
	Irregular Procedure											
F and C with												
B	62	75	69	83	78	95	70	79	71	86	91	95
E and J with												
A	82	85	90	100	100	100	89	96	95	100	100	100
C	82	86	94	92	100	100	86	95	94	92	100	100
A and E with												
B	83	91	89	100	100	100	87	95	94	100	100	100

Predictor	UNDERESTIMATION											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
HEAVY RAIN												
	Y/N						±10					
	Systematic Procedure											
A and C with												
I	77	80	80	88	100	95	87	96	88	91	100	100
J	73	67	68	80	90	89	92	87	80	86	92	89
E and J with												
B	87	85	78	89	88	94	97	98	84	92	91	94
I	85	87	71	90	100	87	90	93	76	90	100	88
A and E with												
B	85	84	79	84	94	97	97	95	83	89	94	97
B and J with												
I	77	81	80	88	95	96	87	96	88	91	95	96
G and C with												
E	86	82	68	89	92	93	97	95	79	89	100	93
I and J with												
C	76	81	79	89	100	96	86	96	88	92	100	96
	Irregular Procedure											
E and J with												
I	72	82	93	89	84	94	76	89	93	89	84	94
I and J with												
C	60	80	78	89	89	100	72	89	82	92	89	100
G and C with												
C	56	74	91	94	92	87	67	87	95	94	92	87

Predictor	O V E R E S T I M A T I O N											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
LIGHT RAIN												
	Y/N						±5					
Systematic Procedure												
A	51	53	57	59	61	56	70	81	69	73	73	77
E	50	65	79	100	92	79	69	80	79	93	100	100
F	44	49	56	67	57	62	68	68	62	63	62	70
H	52	55	65	61	62	60	73	74	73	73	73	73
I	55	56	66	61	63	63	78	76	75	73	76	76
J	59	52	66	61	57	65	83	75	76	74	72	77
K	38	65	71	73	72	81	54	84	77	85	83	95
L	64	75	73	83	73	90	73	92	80	83	82	100
Irregular Procedure												
A	67	63	63	43	57	54	72	78	78	61	67	59
E	79	65	81	71	87	57	86	74	87	71	91	70
F	64	55	61	52	59	64	66	66	72	60	65	70
H	56	53	63	44	49	48	65	66	73	55	59	54
I	55	54	62	46	51	54	66	65	72	58	62	59
J	67	60	65	48	56	58	77	73	77	60	64	62
K	58	47	64	57	67	76	62	62	86	61	72	82
L	64	59	58	65	91	79	71	76	84	71	91	86
HEAVY RAIN												
	Y/N						±10					
Systematic Procedure												
A	56	50	48	48	36	36	84	81	69	60	47	44
B	85	55	62	64	61	74	92	85	79	83	76	78
C	46	46	43	51	41	45	79	71	63	59	54	50
D	47	49	48	57	47	60	75	85	72	73	65	74
G	61	51	60	65	56	63	90	86	83	83	71	73
H	68	57	58	53	40	44	88	83	73	66	53	51
I	69	60	66	47	41	43	91	82	77	56	47	48
J	58	47	49	42	36	40	83	81	69	54	48	48
K	65	51	55	68	57	74	85	84	83	84	72	84
L	56	38	52	64	75	67	89	86	78	89	92	83
M	53	47	55	69	59	79	79	88	77	82	74	89
N	50	45	49	59	44	51	85	82	70	69	65	64

Predictor	OVERESTIMATION											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
HEAVY RAIN (Continued)												
	Y/N						±10					
	Irregular Procedure											
A	33	54	42	52	52	43	48	68	56	58	56	49
B	67	57	49	72	71	76	87	71	68	78	78	76
C	48	48	40	50	39	24	62	60	63	65	47	29
D	57	62	54	66	68	61	70	73	74	77	72	67
G	67	63	59	71	75	69	79	76	79	81	80	76
H	45	55	46	50	50	38	62	67	61	59	55	44
I	39	50	42	49	50	38	54	63	58	57	53	44
J	42	57	46	49	51	39	57	70	61	60	54	45
K	58	66	57	77	77	70	69	79	79	88	83	77
L	56	68	42	70	91	91	72	82	62	85	91	91
M	63	73	62	76	81	71	78	82	81	89	84	82
N	50	64	49	64	71	67	64	78	71	80	73	76
LIGHT RAIN												
	Y/N						±5					
	Systematic Procedure											
A with												
E	67	75	70	100	100	91	67	75	70	100	100	91
F	52	55	65	71	70	69	68	77	70	81	73	81
H	55	64	67	65	71	66	73	86	79	82	85	83
I	54	58	65	61	61	65	71	86	78	77	76	81
J	58	66	66	67	69	66	76	89	77	83	82	83
K	67	87	64	86	67	89	78	88	73	86	78	100
L	64	79	67	71	73	78	82	93	75	88	80	94
E with												
F	50	61	76	92	100	100	74	78	76	92	100	100
H	58	73	81	93	100	91	58	87	81	93	100	100
I	70	73	87	100	100	100	70	82	88	100	100	100
J	58	71	81	92	100	91	58	86	81	92	100	100
K	70	67	83	83	100	100	70	89	83	83	100	100
L	64	69	76	90	100	100	64	83	76	90	100	100
F with												
I	63	57	71	76	65	72	79	74	75	85	71	78
K	64	75	73	83	73	90	73	92	80	83	82	100
L	38	65	71	73	72	81	54	84	77	85	83	95
H with												
I	60	61	71	68	65	69	80	79	80	83	78	91
K	60	73	75	78	73	100	70	91	83	78	82	100

Predictor	OVERESTIMATION											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
LIGHT RAIN (Continued)												
	Y/N						±5					
	Systematic Procedure (Continued)											
I with												
J	64	61	71	68	62	70	85	80	81	83	77	81
K	75	78	77	87	73	100	79	89	85	88	82	100
L	62	74	75	71	72	85	77	89	81	86	83	95
J with												
K	60	73	75	78	73	100	70	81	73	78	82	100
L	44	65	73	67	71	84	61	87	80	81	82	95
K with												
L	64	75	73	83	73	90	73	92	80	83	82	100
	Irregular Procedure											
A with												
E	80	75	88	75	100	69	90	80	100	75	100	85
F	83	85	90	100	100	100	90	96	95	100	100	100
H	66	60	67	42	57	54	73	86	79	82	85	83
I	69	63	65	42	58	59	75	77	81	75	77	81
K	75	58	53	64	89	89	88	75	87	73	89	100
L	58	48	60	50	62	83	67	67	85	56	69	92
E with												
F	78	62	81	73	88	61	83	69	89	73	94	72
H	74	67	83	73	90	60	83	73	86	73	95	75
I	83	57	58	57	56	80	92	93	79	80	67	80
J	83	58	72	70	64	83	92	95	76	81	68	83
K	58	71	75	73	100	77	67	79	92	73	100	85
L	71	65	82	75	100	79	76	70	94	75	100	86
F with												
I	61	74	70	77	82	88	71	80	72	80	93	88
K	64	59	67	62	90	79	71	76	80	69	90	86
L	58	47	64	57	67	76	62	62	86	61	72	82
H with												
K	55	59	61	69	90	85	74	76	86	83	69	90
L	55	47	67	81	79	54	59	62	85	62	72	88
I with												
I	68	65	75	65	73	76	77	72	89	68	77	79
L	66	57	69	47	56	61	77	71	81	59	65	64
K with												
L	62	59	67	60	89	79	69	76	80	67	89	86

Predictor	OVERESTIMATION											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
HEAVY RAIN												
	Y/N						±10					
	Systematic Procedure											
A with												
B	83	59	58	61	59	75	92	90	76	82	72	80
D	60	37	33	54	48	67	80	90	69	74	69	83
G	72	53	57	64	59	70	89	94	86	83	74	81
L	61	52	49	69	59	77	83	91	80	86	74	86
M	75	49	51	69	58	93	92	98	81	81	75	100
B with												
D	89	47	61	69	67	86	89	88	83	85	78	86
G	82	55	62	68	69	86	91	90	82	88	84	86
H	85	60	71	68	62	88	92	95	79	92	71	88
J	71	50	58	60	70	100	86	80	67	90	70	100
K	60	67	62	56	78	90	80	100	88	89	100	90
L	78	57	58	71	71	95	89	93	77	89	89	95
M	89	52	64	77	63	92	100	92	80	91	79	92
C with												
D	45	58	44	54	48	64	80	84	81	71	67	83
G	57	52	57	68	61	60	86	83	85	82	74	67
H	70	74	81	85	97	96	91	90	84	85	97	96
D with												
G	61	51	60	65	56	63	90	86	83	83	71	73
H	63	54	59	62	41	62	84	86	81	81	59	81
K	56	38	54	68	75	67	89	86	81	92	92	83
L	54	41	48	58	59	74	87	84	86	81	70	87
M	60	42	55	60	72	77	80	92	86	80	83	92
N	50	48	50	61	51	61	82	85	77	74	66	76
G with												
H	70	60	69	66	54	65	93	87	83	87	65	74
J	77	60	74	67	58	63	95	88	85	82	66	70
L	73	53	58	68	62	79	91	87	85	86	79	90
M	60	48	61	72	68	93	92	90	82	87	79	93
H with												
J	74	61	69	51	45	45	92	85	80	61	52	61
L	79	54	63	70	60	80	95	86	83	90	72	90
M	72	60	69	63	64	75	100	90	88	80	73	92
N	60	56	61	62	46	57	95	86	82	71	65	75
I with												
L	69	53	60	47	35	45	88	84	76	62	47	56
N	61	52	52	60	60	75	83	89	83	80	70	90

Predictor	OVERESTIMATION											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
HEAVY RAIN (Continued)												
	Y/N						±10					
Systematic Procedure (Continued)												
J with												
L	74	58	64	72	67	80	89	88	82	88	76	87
M	73	64	70	67	60	87	93	93	89	78	70	88
K with												
L	50	44	61	63	87	73	83	83	94	89	100	93
N	62	39	56	78	77	67	100	86	80	91	91	80
L with												
M	72	49	58	73	68	93	89	89	84	87	76	93
M with												
N	53	47	55	69	59	79	79	88	77	82	74	89
Irregular Procedure												
A with												
B	58	53	50	71	68	75	92	90	76	82	72	80
D	56	69	49	62	70	54	81	80	64	67	70	68
G	68	64	58	72	76	68	79	77	72	77	80	76
L	59	66	58	79	80	84	83	91	80	86	74	86
M	69	75	58	71	85	64	85	83	77	86	85	82
B with												
D	62	55	35	74	83	89	88	75	65	79	83	89
G	83	61	59	81	78	81	100	79	79	83	83	81
H	67	59	53	69	76	76	87	73	68	76	82	76
I	80	61	56	71	70	77	100	78	74	79	76	77
K	57	55	44	80	100	90	86	82	78	90	100	90
L	89	93	77	89	89	95	91	79	78	89	88	86
M	78	73	62	87	92	86	100	82	81	93	92	86
C with												
G	68	44	52	65	71	56	80	64	74	81	79	67
D with												
G	63	69	46	66	80	75	79	86	76	80	83	83
H	54	67	54	62	66	52	69	79	72	72	69	58
K	56	68	42	70	91	91	72	82	62	95	91	91
L	50	67	45	71	77	75	64	82	72	89	81	85
M	57	81	52	70	76	67	71	83	76	83	81	83
N	52	67	48	62	71	59	70	81	72	77	73	70
G with												
H	65	63	60	71	78	69	78	76	78	80	81	77
L	64	64	61	80	76	75	77	77	80	87	82	82
M	62	76	62	81	81	67	79	85	79	90	85	83

Predictor	OVERESTIMATION											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
HEAVY RAIN (Continued)												
	Y/N						±10					
	Irregular Procedure (Continued)											
H with												
K	56	67	42	78	91	91	75	81	88	94	91	91
M	60	67	61	76	82	72	72	80	78	86	84	79
N	62	72	61	75	83	71	77	81	80	88	87	82
I with												
K	65	74	55	59	64	53	83	88	73	72	64	54
J with												
L	57	66	60	76	83	82	70	78	77	86	83	79
M	61	74	61	75	86	71	78	83	78	86	86	82
K with												
L	50	64	43	79	87	90	64	82	71	100	88	90
N	56	68	42	68	90	87	72	82	68	95	90	88
L with												
M	62	69	57	79	78	55	81	78	77	88	83	73
N with												
N	63	73	62	76	81	71	78	82	81	89	84	82
LIGHT RAIN												
	Y/N						±5					
	Systematic Procedure											
A and I with												
L	67	83	70	69	73	82	78	92	78	88	80	94
I and J with												
F	64	62	72	78	62	69	79	78	77	88	69	76
H	65	63	72	71	64	69	84	82	81	87	78	80
I and L with												
H	44	65	73	67	71	84	61	86	80	81	82	98
	Irregular Procedure											
E and J with												
H	65	67	85	79	94	71	76	74	89	79	94	82
K	50	67	80	80	100	83	60	75	100	80	100	92
L	64	65	87	82	100	85	71	71	100	82	100	92
E and H with												
I	83	70	88	77	100	80	100	76	92	77	100	87
L	67	65	87	75	100	85	73	70	94	75	100	92

Predictor	O V E R E S T I M A T I O N											
	Sampling Intervals											
	10	15	20	30	40	50	10	15	20	30	40	50
LIGHT RAIN (Continued)												
	Y/N						±5					
	Irregular Procedure (Continued)											
H and J with												
E	65	67	85	79	94	71	76	74	89	79	94	82
H	65	63	72	71	64	69	84	82	81	87	78	80
HEAVY RAIN												
	Y/N						±10					
	Systematic Procedure											
B and G with												
D	71	62	55	58	71	93	86	100	91	92	86	93
H	82	61	73	70	68	93	91	100	82	77	93	100
L	57	60	71	71	95	80	89	93	80	89	89	95
N	86	62	57	73	64	92	100	100	86	91	86	92
B and H with												
C	89	58	71	69	67	86	89	100	86	85	78	86
L	78	61	68	70	74	100	89	100	77	90	84	100
M	89	59	76	72	69	100	100	100	82	89	75	100
N	86	67	64	67	70	100	100	100	82	89	80	100
G and L with												
H	78	56	67	68	60	80	94	88	85	89	72	90
K	50	44	59	59	87	73	83	83	94	88	100	93
	Irregular Procedure											
B and G with												
D	71	61	43	76	87	94	100	87	79	82	88	94
L	80	61	62	86	84	86	100	79	83	89	88	86
M	78	71	62	86	92	86	100	81	81	93	92	86
B and H with												
L	73	64	62	83	91	86	91	82	79	88	91	86
M	78	73	67	82	100	86	100	82	80	91	100	86
D and J with												
L	54	67	50	73	80	75	69	82	69	88	80	85
G and I with												
M	60	77	59	78	81	67	80	85	74	87	81	89

APPENDIX B

The critical values which variances are compared against in order to determine whether or not homogeneity existed are listed. The critical value to be used is a function of the sample size.

Sample Size	Critical Value
2	39.8666
3	8.5264
4	5.5366
5	4.5454
6	4.0602
7	3.7752
8	3.5910
9	3.4596
10	3.3599
11	3.2833
12	3.2256
13	3.1755
14	3.1364
15	3.1011
16	3.0730
17	3.0485
18	3.0276
19	3.0068
20	2.9894
21	2.9756
22	2.9618
23	2.9481
24	2.9378
25	2.9275
26	2.9173
27	2.9104
28	2.9002
29	2.8934
30	2.8866

VITA

Vincent Patrick Holbrook was born in San Antonio, Texas on 10 May 1955 to Francis M. and Rosemary Holbrook. He graduated from East Central High School, Sayers, Texas in 1973. He attended San Antonio College for two years then transferred to Texas A&M University where he received a Bachelor of Science in Meteorology in 1979.

The author attended Officer Training School at Lackland Air Force Base and was commissioned in April 1980. From there, he completed a three year assignment at Fort Hood, Texas serving as a staff weather officer. In 1983, he was transferred to Air Force Global Weather Central at Offutt Air Force Base and served as a computer systems duty officer. The author reentered Texas A&M, through AFIT sponsorship, in 1986 to pursue the degree of Master of Science.

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